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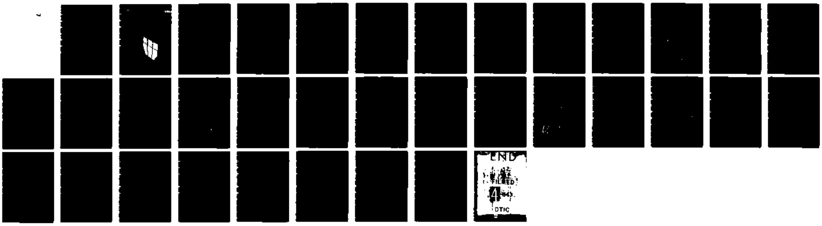

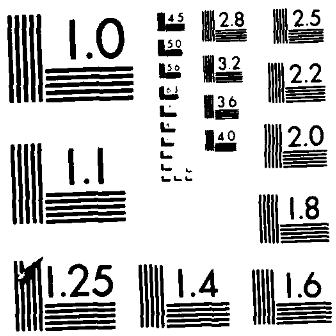

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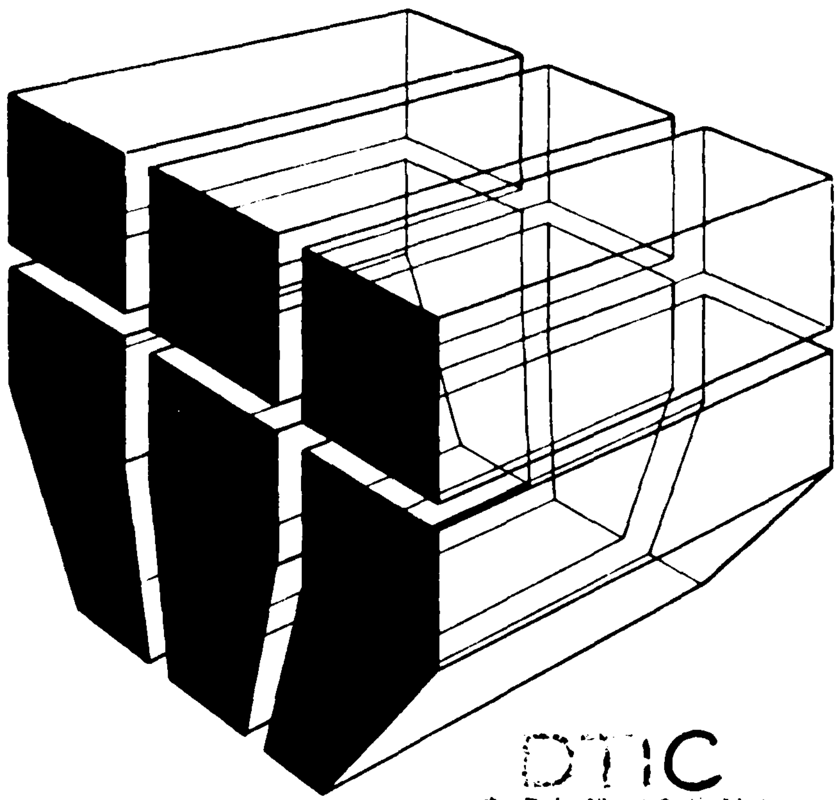
Technical Report E-1
December 19

WIND POWER GENERATION DESIGN CONSIDERATIONS

by
Elizabeth Elischer
Larry M. Windingland



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Guidance is provided for the design of a wind power generation system suitable for Civil Works operational sites. The choice of components for a given system is discussed in terms of the highest efficiency possible at the proposed site. Guidance also is given for site selection to minimize environmental impact and maximize the rotor's wind exposure.

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FOREWORD

This study was performed by the Energy Systems (ES) Division of the U.S. Army Construction Engineering Research Laboratory (CERL) for the Directorate of Civil Works, Office of the Chief of Engineers (OCE), under IAO CWO-M-82-17. The OCE Technical Monitor was Jack Bickley, DAEN-CWO-M.

R.G. Donaghy is Chief of CERL-ES. COL Paul J. Theuer is Commander and Director of CERL, and Dr. L.R. Shaffer is Technical Director.

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WIND POWER GENERATION DESIGN CONSIDERATIONS

1 INTRODUCTION

Background

Windmills were used as a source of mechanical energy by Chinese and Persian civilizations. Wind turbines generating electricity were developed and constructed from the late 1800s through the 1950s, but none could operate competitively with coal- and oil-fired steam plants.[1] Since 1973, however, interest in wind power generation systems has been renewed because of the increasing cost of electrical energy. As part of the Army's goal to conserve energy,[2] a number of experimental wind power generators have been developed through a Federal wind-energy program. These generators, which have been constructed and tested successfully, have output ratings of 100 kW, 200 kW, 2.0 MW, and 2.5 MW.[3] Wind power generation systems with output ratings ranging from .5 kW to 25 kW can be purchased commercially. Wind power generators can potentially supplement electrical energy cost-effectively at some Civil Works operational sites. However, not all sites are feasible choices for the use of such systems because certain physical factors would limit the generator's performance. Thus, guidance is needed for site selection.

Objective

The objective of this report is to provide guidance for site selection and design considerations of a wind power generation system suitable for Civil Works operational sites.

Approach

Existing documentation on wind power generators was reviewed. Pertinent information was extracted which related to wind power generation system design criteria at Civil Works field operating activity sites.

[1] D. Pal, *Wind Power Utilization Guide* (Port Hueneme: Naval Civil Engineering Laboratory Press, 1981), p 1.

[2] ER 11-1-D, *Corps of Engineers Energy Program* (U.S. Department of the Army (5 April 1982).

[3] Michael G. McGraw, "Wind-Turbine Generator Systems," *Electrical World* (May 1981), p 98.

2 TYPES OF WIND POWER GENERATORS

Two main types of wind power generators are now used: the horizontal axis type and the vertical axis type. The most common is the horizontal axis system, which has an axis rotation parallel to the wind flow. Figure 1 shows the main components of a horizontal wind power generator. In a generic wind power generator system, blades develop torque due to wind flow causing low speed hub rotation (below 200 rpm). To match the rated speed of an electric generator, a transmission would increase rotation to about 1800 rpm.[4] Because of the variable nature of the wind, the electricity generated has variable voltage and frequency. Therefore, the generated electricity is delivered to a power conditioner, which provides constant-voltage synchronous power for use or storage. To capture maximal wind power, the system must be able to follow wind direction by means of a rotating tower or a rotating bed plate. Restrictions can be placed on the main shaft and the blades to stop or control blade rotation. A brake installed along the main shaft stops blade rotation when activated either manually during maintenance shutdown or automatically when the turbine exceeds speed limitations. Other restrictions controlling turbine rotation speed include changing blade pitch, flaps or spoilers on the blade surfaces released by a centrifugal switch, and full aerodynamic blade stall.

The vertical axis wind generator has an axis of rotation normal to the wind flow. Figure 2 shows classifications of vertical axis systems: the Darrius, which is the most common vertical axis system; the Savonius; and the cycloturbine. Darrius-type rotors, composed of curved blades with airfoil cross sections, have low starting torques, operate at high tip-to-wind speeds, and generate high power output per turbine weight.[5] The Savonius rotor operates when the wind encounters the concave side, circulates through the center to the back of the convex side, and generates a negative pressure creating additional torque on the rotor. The cycloturbine controls blade pitch by a cam device: this device operates according to a preset schedule of angles to use the aerodynamic forces on the blades most favorably.

The components of a vertical axis system are similar to those of a horizontal axis system with the

[4] D. Pal, p 76.

[5] D. Pal, p 82.

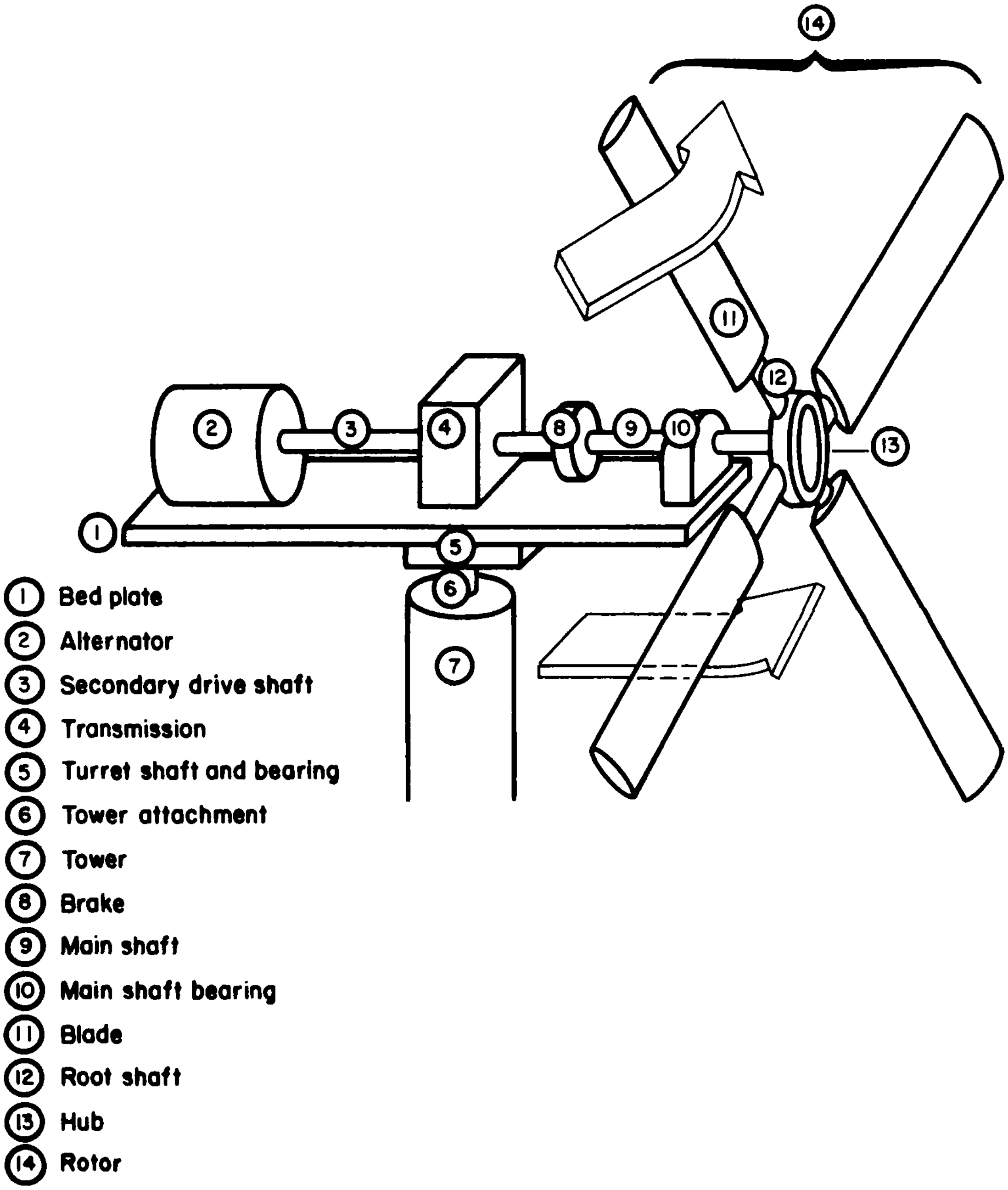

Figure 1. Mechanical components of a typical horizontal wind power generator. (Adapted from D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 81.)

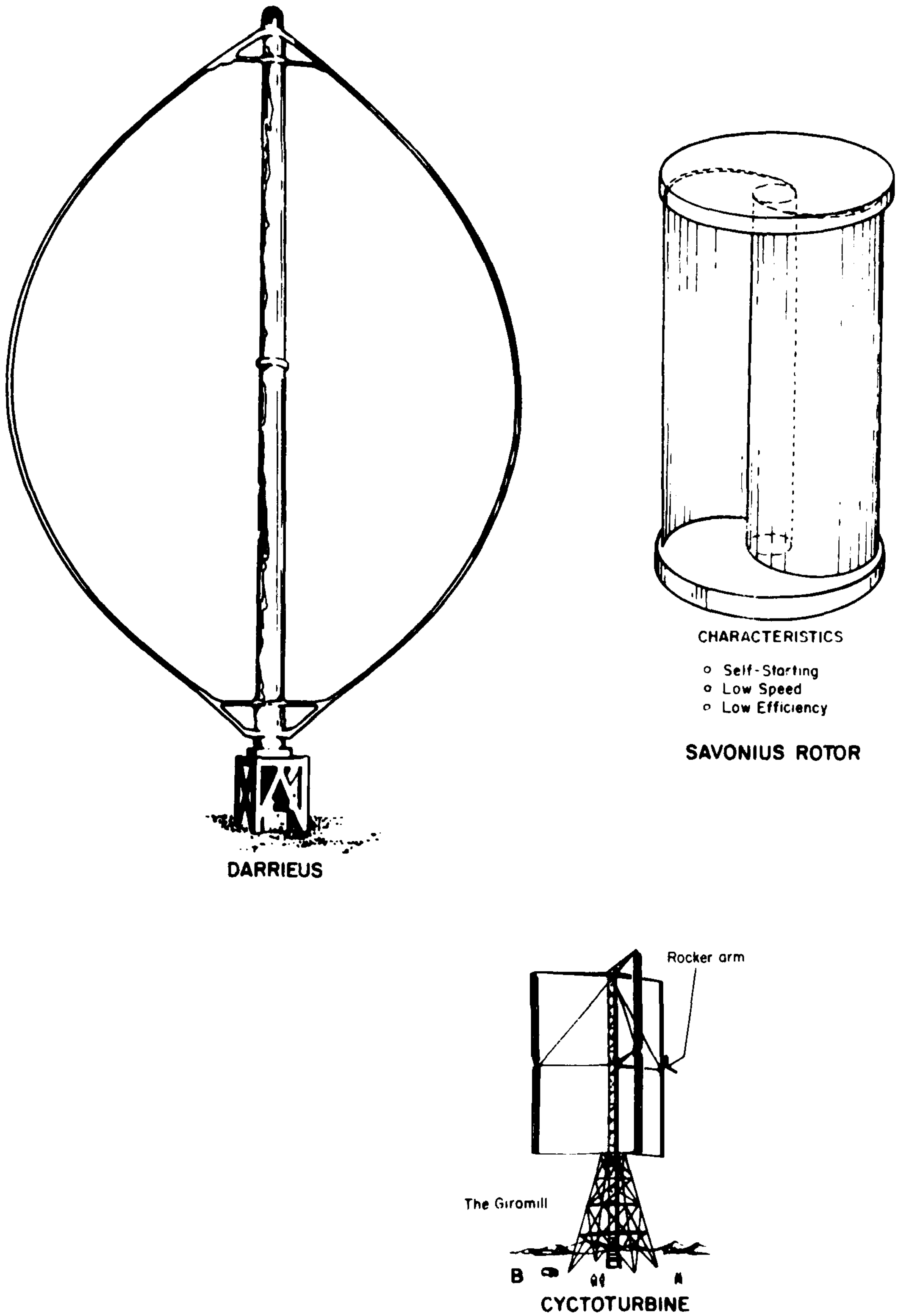

Figure 2. Three classifications of vertical axis systems. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], pp 71, 82.)

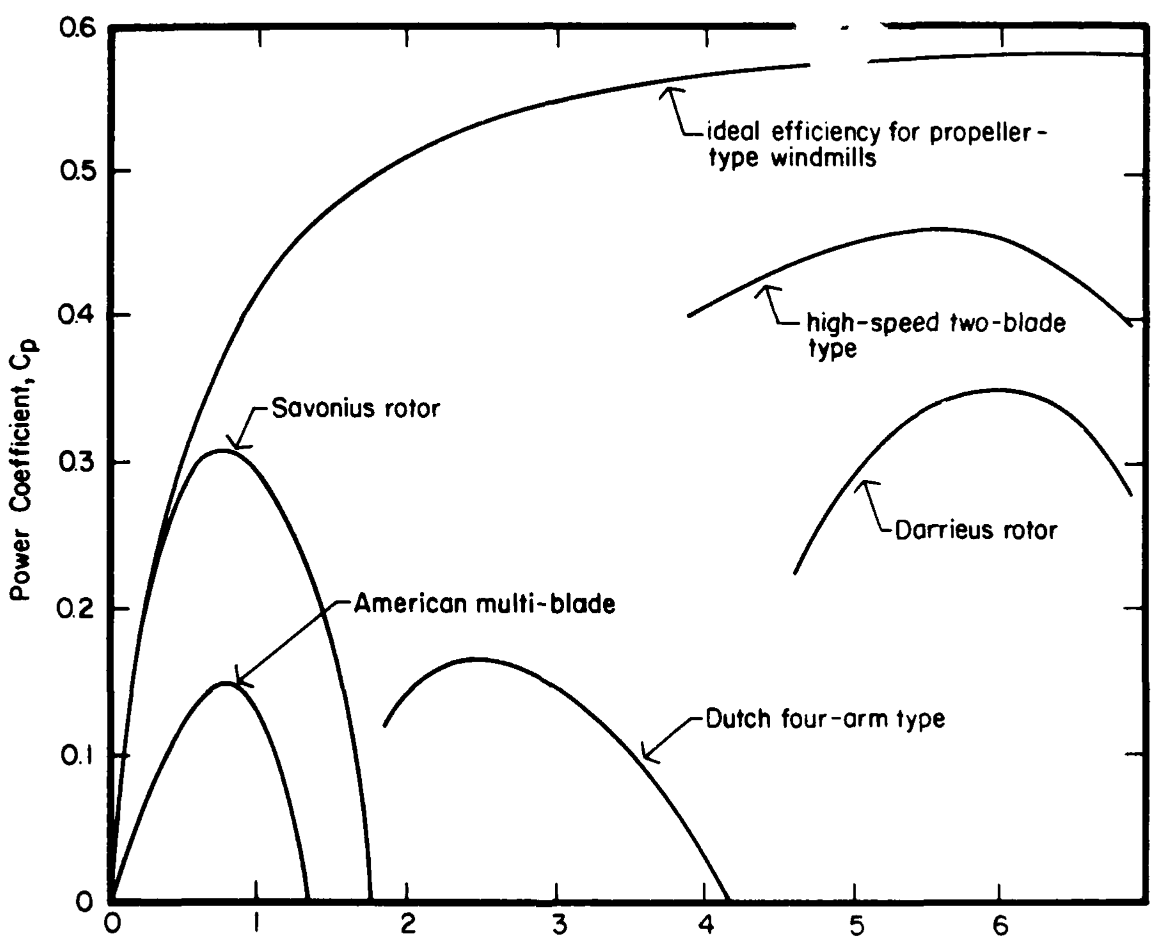

Figure 3. Ratio of blade tip speed to wind speed. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 74.)

following exceptions. First, the transmission and generator, which are turbine-activated, can be located close to the ground, which leads to less expensive maintenance and allows simple tower construction. Second, a rotating tower or bed plate is not needed because vertical axis systems can accept wind from any direction. Third, fabrication costs tend to be lower, and increasing the scale of the generator structure for a greater output power rating is easier.[6] Table 1 summarizes further differences between the two types of wind turbines. Figure 3 shows power efficiencies for the most common horizontal- and vertical-type systems.

Wind power generators can also be classified according to size. Small wind power generators usually produce less than 20 kW and may or may not have storage. They can supply energy for one to three residences or for a small commercial establishment. Medium-capacity wind power generators produce 20 to 200 kW and can be used in commercial operations, multi-family residences, and light industry. Large wind power systems, generating 200 kW to 4 MW, are used by heavy industry, large-scale commercial operations, and utility companies.

Size, type, design, and location affect the operation and maintenance costs of a wind power generation system. Limited data based on operational equipment in Denmark reveal the following operating and maintenance costs: plants up to 10 kW accrue 3 to 5 percent of equipment capital costs; plants from 10 kW to 20 kW accrue 2 to 5 percent of capital costs; plants from 20 kW to 100 kW accrue 1 to 2 percent of capital costs; and plants greater than 100 kW expend about 1 percent of the capital costs.[7] The overall useful life of a wind power generation system is estimated to be 25 years; however, individual components may fatigue sooner. Table 2 gives guidelines for the technological lives of wind power generation system components.[8]

Table 1
Wind Turbine Characteristics

Item	Horizontal Axis	Vertical Axis
Direction dependence	Yaw mechanism fixed or active	Nondirectional
Self-starting	Yes	Some
Support	Tall, rigid structure	Wires and foundation
Maximum efficiency	45%	51%
Pitch control	Optional	Optional
Lift or drag type	Both	Both

Table 2
Maximum Economic Life

Wind turbine rotor blades	5 to 10 Years
Wind turbine mechanical components	20 to 25 Years
Wind turbine tower storage batteries	4 to 5 Years

3 DESIGN STUDIES

Several studies should be completed before a wind power generator is procured. First, candidate sites should be selected which are close to the point of power consumption, have the least environmental impact, and are exposed to the maximum available wind. Second, monthly wind velocities at the site should be evaluated to determine the available wind power. If weather data for the area do not accurately represent the site conditions, more data may have to be collected to determine true wind speeds. Third, the power generator capacity depends on the size of the generator rotor and the wind velocity. Therefore, to determine the size of the wind generator rotor needed, energy load requirements should be estimated on a monthly basis. These values should then be compared with wind velocities at the site to calculate the appropriate rotor size.

After the system size has been established, the tower, system components, and power conditioning equipment should be selected. Finally, an economic analysis should be performed evaluating the life cycle cost of the selected system. Methodology similar to the National Bureau of Standards "Savings to Investment Ratio" should be used to establish project feasibility.[9]

4 SITE ANALYSIS: ENVIRONMENTAL CONSIDERATIONS

Because improper siting is the major cause of dissatisfaction to users of small wind power generators, location should be thoroughly analyzed before

[6] D. Pal, p 85.

[7] D. Pal, p 138.

[8] D. Pal, p 139.

[9] Harold E. Marshall and Rosalie T. Ruegg, *Simplified Energy Design Economics*, Publication 544 (Washington, DC: National Bureau of Standards, 1980), p 11.

constructing a wind power generator.[10] When considering installation of a wind system, the following two problems must be solved:

1. Finding an acceptable location for the system within a given area.

2. Accurately estimating wind characteristics at each candidate site to determine the optimal location.

The general location for a wind power generator should be close to the point of power consumption. Generally, the land area required for a tower of a small-scale wind system (5 to 30 kW) is 225 sq ft. The area for a 1.5-MW turbine is estimated to be 21,780 sq ft (.5 acres).[11] Also, a wind generator location should not conflict with logistics or the installation's mission and must consider legal constraints such as land zoning laws.

Environmental impacts of the wind power generator on the surrounding area should be studied in depth before a location is selected. For example, recent studies show that large wind systems can cause noise disturbances.[12] When blades pass through wakes downstream of the tower vertical support members, nearby residents report a low thumping noise and vibrations. However, small wind systems have not been known to cause these disturbances.

Wind systems can also cause reception difficulties in television video signals, up to 1 4 mile from the VHF signal and 3 miles from the UHF signal.[13] As the TV channel frequency increases, interference of video signals increases. Interference problems may be resolved by placing the wind generator system in an isolated cardioid-shaped area (see Figure 4).[14] A large rotor blade and a high-frequency transmittal require a larger area, but the cardioid shape remains the same for various sizes of wind power generators. Since most TV signals are horizontally polarized, television interference is less of a problem for vertical-axis systems than for horizontal-axis systems.[15]

Microwave communication links and electromagnetic transmission may be altered when signals come in contact with the rotating wind generator blade and scatter into secondary interference signals.[16] Federal Communications Commission (FCC) guidelines should be used to curtail significant electromagnetic transmission interference. The radiation pattern of the receiving antenna determines the shape of the zone around the microwave-link receiver within which wind generators should not be located (Figure 4).

Soil erosion, water pollution, and disturbances of plant and animal species may arise if forest areas are cleared to increase wind flow on blade surfaces. When a wind system is placed on coastal regions, topsoil and vegetation erosion may occur, causing slope failure and disruption of the coastal sediment transport system.[17]

5 SITE ANALYSIS: WIND CHARACTERISTICS

After candidate sites for the wind power generator have been found, the wind characteristics at each should be determined to establish the optimal location. First, the prevailing wind direction of the area should be identified. This can be determined through wind summaries provided by the local weather station or from measurements at the location. Next, the terrain over which the wind flows should be studied. Changes in terrain, discontinuities in surface texture, and man-made structures are factors which affect ground winds. When determining the site's wind characteristics, one must understand how these obstacles disturb winds; this will show the region of maximum wind velocity and avoid the problem of siting the generator in a region of low wind speed. In general, wind power generators are best applied at remote sites where average wind speeds exceed 10 mph. The generators should be exposed to the maximum available wind.

For most wind generation systems, high wind speeds (greater than 45 mph) may produce conditions requiring wind generator shutdown to avoid damage.[18] Obviously, calm conditions render a wind power generation system inoperable. Calm spells generally occur during 30 percent of the year at a site

[10] D. Pal, p 119

[11] Mark L. Hasset, *Wind Energy in Michigan* (Ann Arbor: University of Michigan, 1982), p 62

[12] Neil Kelley, "Wind-Turbine Noise Research at SERI," *In Review* (May June 1982), p 6.

[13] Mark L. Hasset, p 60.

[14] Michael G. McGraw, p 110.

[15] Michael G. McGraw, p 110.

[16] Michael G. McGraw, pp 109-110

[17] Mark L. Hasset, p 59

[18] D. Pal, p 45

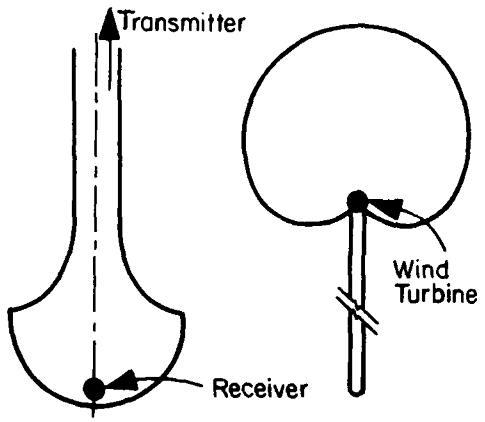

Figure 4. Interference with microwave and TV reception caused by wind turbines can be avoided by siting the wind turbine generator clear of forbidden zones left for a microwave-link receiver and right for TV. (From Michael G. McGraw, "Wind Turbine Generator Systems," *Electrical World* [May 1981], p 108.)

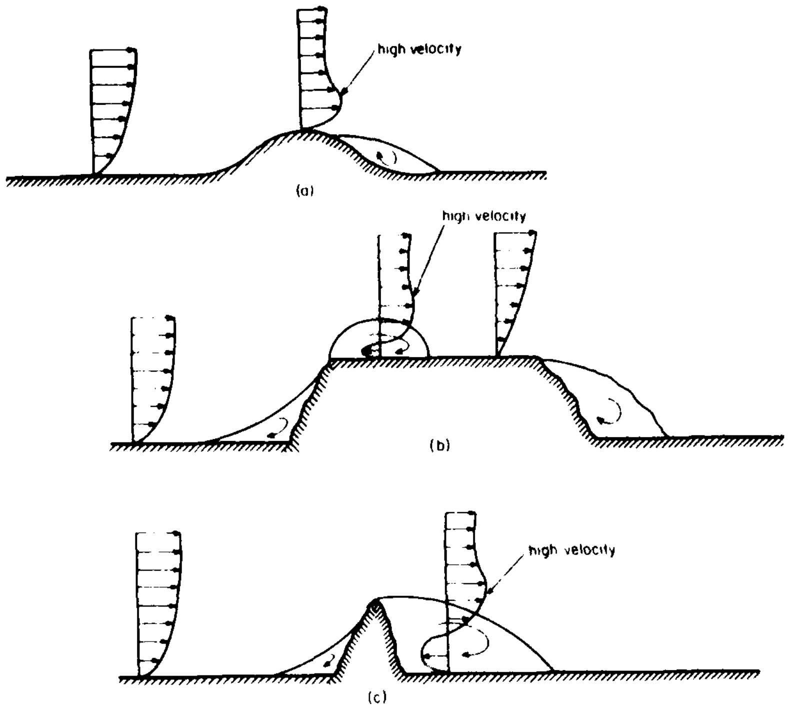

Figure 5. Typical flow patterns over two-dimensional hills. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 23.)

with an annual mean wind speed of 7 mph and during 3 percent of the year at a site with an annual mean wind speed of 25 mph. A loss of energy generation from calm or high wind speed conditions results in higher storage requirements and lower system efficiency.

Hills and Mountains

Hills can be divided into two categories:

1. *Two-dimensional* hills are long: the wind is perpendicular to the side of the hill. Figure 5 shows typical wind flow patterns around two-dimensional hills. The maximum wind flow occurs at "approximately half a hill height above the hilltop and the magnitude of these winds is equivalent to wind velocities at three hill heights over level ground."[19] (See Figure 6.)

2. *Three-dimensional* hills, as shown in Figure 7, have reduced wind speeds at the hilltop and high wind speeds down the lee side of the mountain.[20]

The advantage of siting a wind power generator on top of a two-dimensional hill is that the hill acts like a large tower, which puts the generator in an area of higher wind velocity. Placing a wind power generator on the leeside of a three-dimensional mountain is advantageous, since wind flow in this region is accelerated; as a result, increased wind power is available. Elevated terrains upwind of a wind power generator site are a disadvantage, since they could totally obstruct high winds from the site or cause excessive turbulence and wind gusts.

Valleys, Canyons, and Passes

A prevailing wind flowing parallel to a valley, canyon, or mountain pass may cause a tunnel effect; this would increase wind velocity, especially where the depression narrows or where its sides become steeper. However, this effect does not always occur. If the valley or pass is in a relatively short ridge, the wind could blow around the ridge and not through the gap. Likewise, if a valley is in a ridge and is sheltered by surrounding hills, there may be no tunnel effect.

When the prevailing winds blow at right angles to the valley, the flow down the lee side of the mountain increases during stable atmospheric conditions. However, during neutral atmospheric conditions, the prevailing wind perpendicular to the valley can form a recirculating eddy on the lee side[21] (see Figure 8).

Thermally driven circulation, such as that found along coastlines, occurs in depressions; this results in winds that flow in and out of basins or up and down sloping mountain valleys. Another condition conducive to enhanced wind velocity is when a mountain range separates two distinct air masses, as along the West Coast of the United States. Cool, dense, marine air is separated from warmer, less dense interior air. This causes strong pressure gradients across the mountains which create high winds through many of the passes.

Man-Made Structures

Wind flow will separate before it touches the edge of a man-made structure. There is usually a large, recirculating eddy on the lee side of the building; from here the wind flow reattaches about 16 building heights downstream of the initial separation. Figure 9 shows this pattern and the recovery of velocity at various heights and distances from the building. The higher off the ground that reattachment occurs, the sooner wind velocity recovers behind an obstacle. Therefore, if a wind power generator must be located downwind of a man-made structure, the generator should be either tall enough to protrude outside the recirculating region or located far enough downstream that wind flow is reattached before it reaches the generator blades.

Surface Discontinuities

A change in surface roughness will occur where the sea or lake meets the shore, where a forest meets a plain, or where the city edge joins a rural community. A surface texture changing from rough to smooth or from smooth to rough forms an internal boundary layer where wind flow is altered. Figure 10 shows the altered wind flow and the most advantageous site positions within these wind profiles.

Flat Terrain

Flat terrain is defined as land whose "maximum terrain relief (h) is less than 200 feet within a 2.5 mile radius of the site" and whose wind power generator "is at least 2 h to 3 h above ground."[22] (See Figure 11.) Flat terrain is homogeneous if the surface roughness is uniform $^1/_2$ mile upwind of the site. Here, wind velocity can be increased only by increasing the tower height. Flat terrain is not homogeneous if there are obstacles or changes in the surface roughness upwind of the location. If the area is not homogeneous, the options available to increase wind speed include

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[19] D. Pal, p 25.

[20] D. Pal, p 26.

[21] D. Pal, p 26.

[22] D. Pal, p 123.

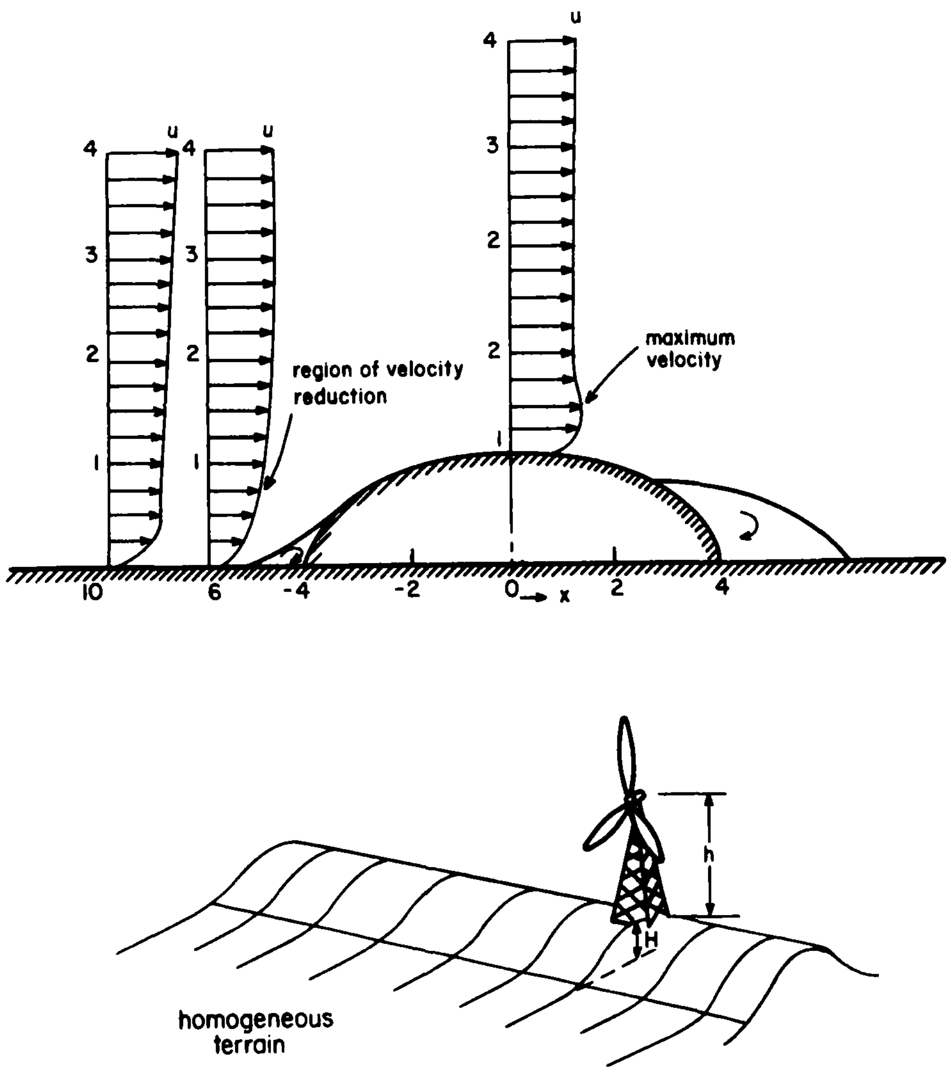


Figure 6. Wind flow over two-dimensional elliptical hill. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 24.)

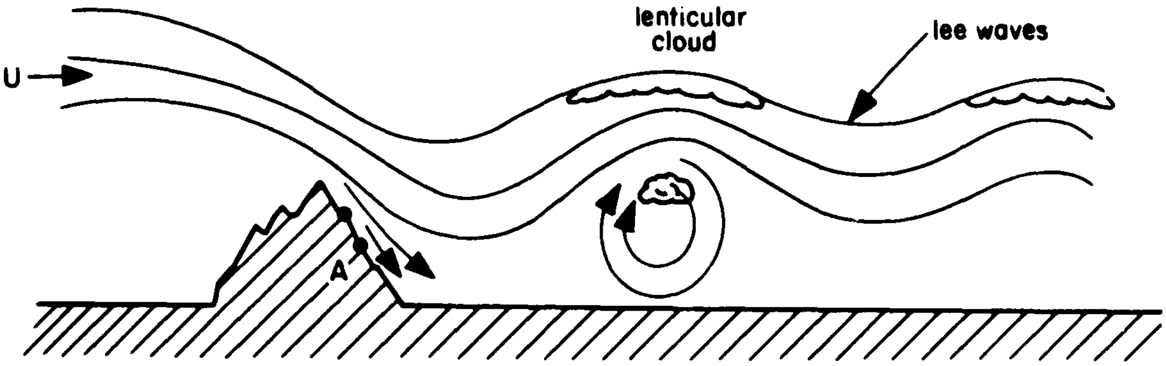


Figure 7. Lee waves forming behind a mountain. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 25.)

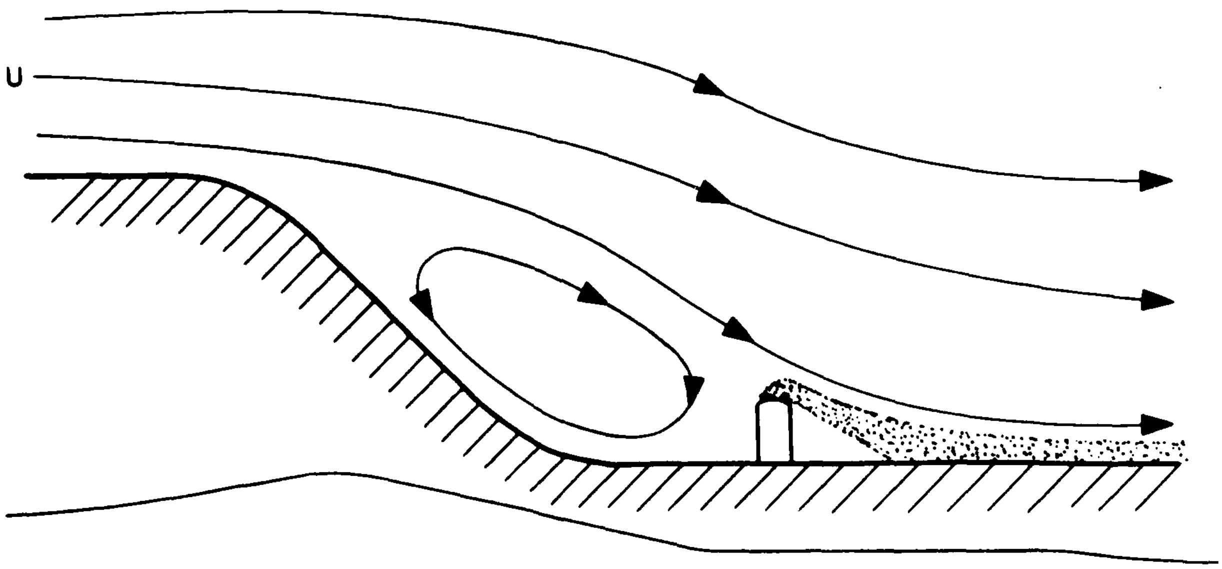


Figure 8. Schematic representation of downwash in a valley. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 26.)

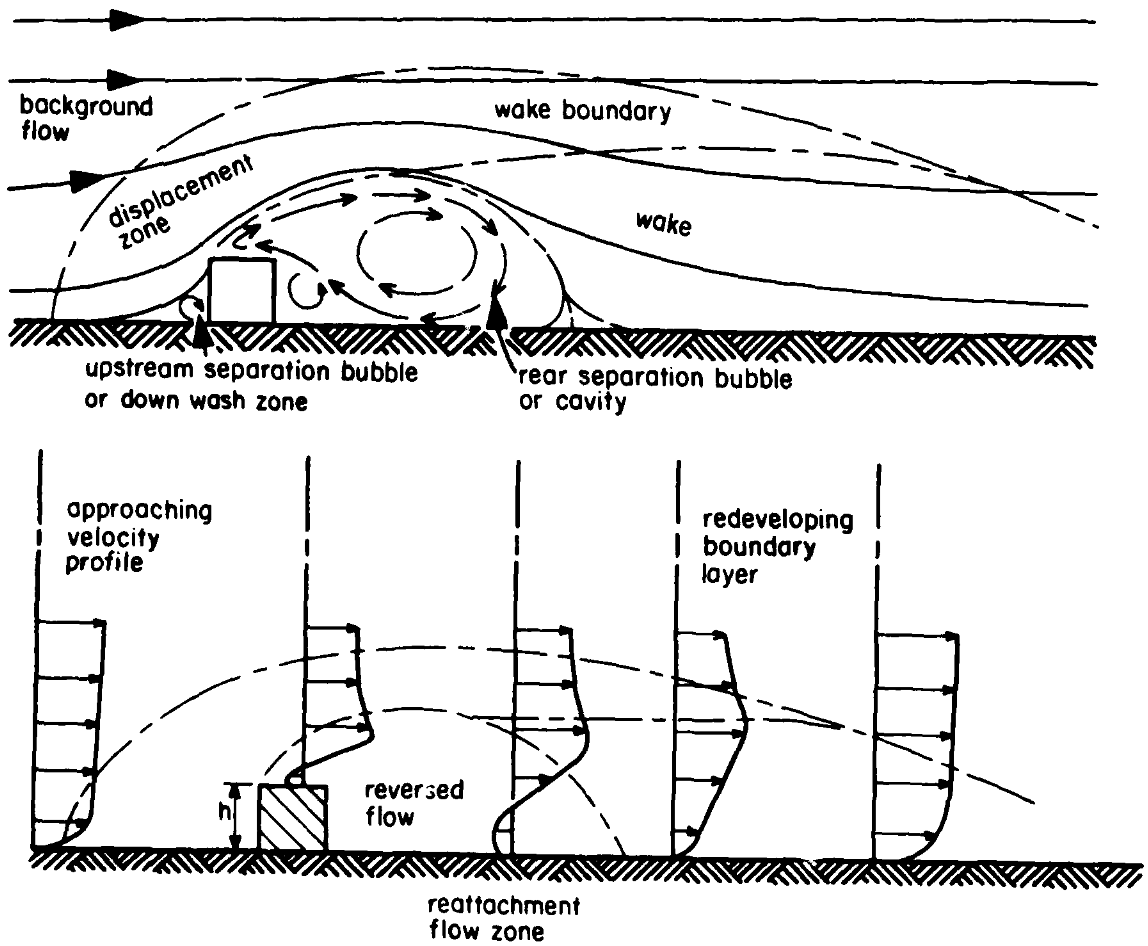


Figure 9. Definition of flow zones near a sharp-edged building. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 27.)

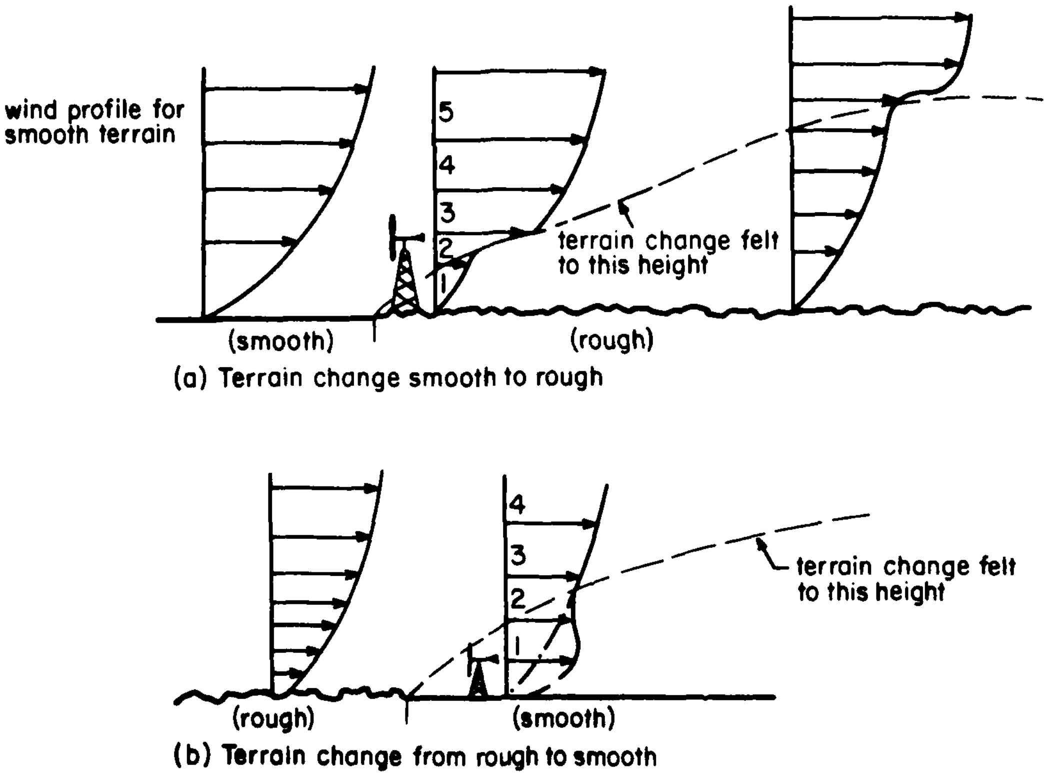


Figure 10. Wind speed profiles near a change in terrain. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 129.)

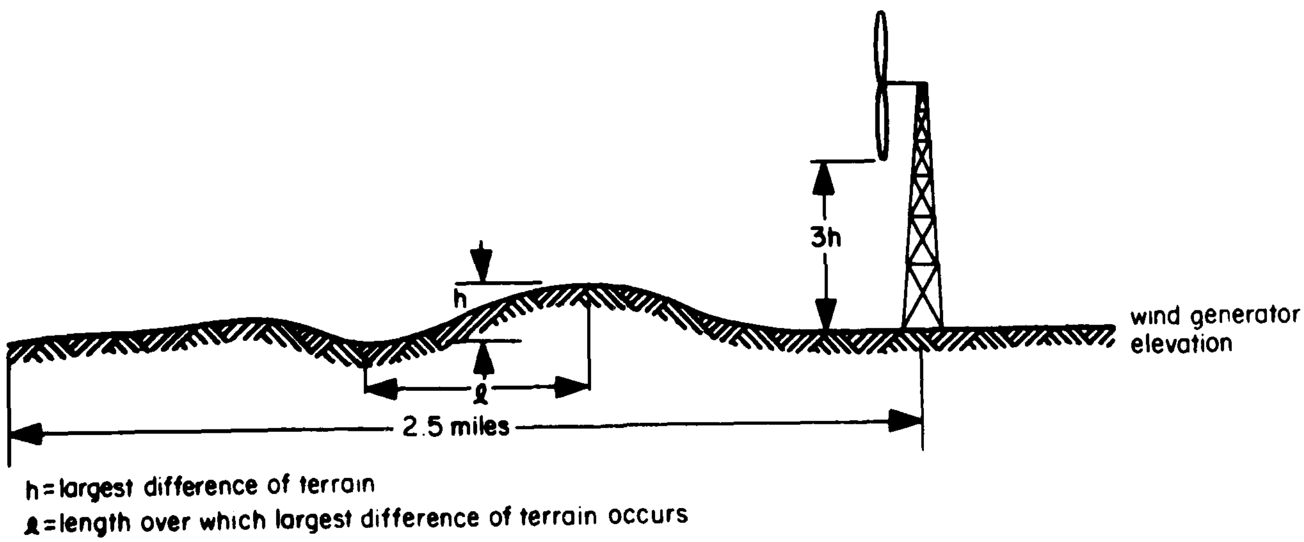


Figure 11. Determination of flat terrain. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 125.)

1. Locate the site along the prevailing wind direction upwind from all barriers.

2. Site the machine outside the barrier flow disturbance by locating it far enough upwind or downwind of the obstacle (see Figure 9).

3. Take advantage of the change in surface roughness, which produces the wind speed profiles shown in Figure 10.

4. Place the turbine above the flow disturbance if the obstacle is unavoidable (see Figure 9).

In summary, wind speed may vary greatly within a short distance around elevated terrain, depressions, man-made obstacles, and surface discontinuities. The best approach to site selection in a complex terrain is to first analyze the effects of the various topographical features in descending order of size. Once the effects of the topographical features have been assessed, the effects of any obstacles and surface discontinuities should be considered to find the optimal location.

6 WIND POWER CALCULATIONS

When the optimal site for a wind power generator is selected, available data should be evaluated to determine the available wind power. Power available from the wind is defined as "the kinetic energy of a column of air moving undisturbed through a finite rotor disc area."[23] Thus, wind power output depends on both wind velocity and the wind power generator's rotor size. Accurate estimates of wind velocity are needed throughout the year to determine the size of the wind power rotor required to meet the consumer's electrical load demands.

Wind data sources include the National Weather Service, the National Forest Service, local electric utility companies, state and local agencies concerned with air pollution, nuclear power plants, and colleges or universities.[24] Data needed for wind power calculations are:

1. *Site wind speed summaries*. These provide tables of wind speeds for each month and the annual average distribution of these speeds.

2. *Air density annual mean value*. Air density can be calculated by obtaining the annual mean dry bulb temperature value and the site elevation. When performing monthly calculations for wind power potential, only the annual mean value of the air density must be used.[25]

Existing weather data for an area might not accurately represent the generator site conditions because of topographical differences. If this is the case, the site should be further analyzed to accurately determine its wind velocity. Table 3 lists the approach, advantages, and disadvantages of three methods to estimate the site wind speed.

[23] D. Pal, p 7.

[24] D. Pal, p 120.

[25] D. Pal, p 11.

Table 3
Methods of Site Analysis for Wind Power Generators

Method	Approach	Advantages	Disadvantages
A	Use wind data from a nearby station: determine power output characteristics.	Little time or expense required for collecting and analyzing data. If used properly, can be acceptably accurate.	Only works well in large area of flat terrain where average annual wind speeds are 10 mph or greater.
B	Make limited on-site wind measurements and establish rough correlations with nearby stations; then *compute power output* characteristics.	If there is a high correlation between the site and the station, this method should be more accurate than the first method.	Of questionable accuracy, particularly where there is seasonal modulation of wind speeds and directions.
C	Collect wind data for the site and analyze it to obtain power output characteristics.	Most accurate method. Works in all types of terrain.	Requires at least a year of data collection. Added costs of wind recorders. Data period must represent typical wind conditions.

The available wind power, Pa (in watts), can be calculated as:[26]

$$Pa = \frac{1}{2}\rho A v^3 \qquad [Eq\ 1]$$

where ρ = annual mean air density (kg/m^3)
A = area swept by the rotor normal to the wind (m^2)
v = monthly or annual mean wind velocity (m/s).

Annual mean air density can be calculated as:[27]

$$\rho = B/5.989(D+273.15) \qquad [Eq\ 2]$$

where B = barometric pressure at the site elevation (lb/sq ft) (see Table 4)
D = annual mean dry-bulb temperature (°C).

Finally, to convert wind velocity units from miles per hour to meters per second, multiply velocity by a factor of 0.447.

The area swept by the rotor (i.e., the size of the wind system) should be determined by comparing the power available in the wind and the electrical power demanded by the consumer. Therefore, power available from the wind is usually given in units of watts per square meter or watts per square foot and is equal to $^1/_2\ \rho v^3$. Figure 12 gives an overview of wind power potential for different areas of the nation. These estimates may differ from onsite calculations because of topographical effects. To convert wind power potential from watts per square meter to watts per square foot, multiply power potential by a factor of .0929.

Table 4
Properties of Standard Atmosphere

Altitude (ft)	Pressure (lb/sq ft)
0	2,116
1,000	2,040
2,000	1,967
3,000	1,896
4,000	1,827
5,000	1,760
6,000	1,696
7,000	1,633
8,000	1,571
9,000	1,512
10,000	1,455

[26] D. Pal, p 7.
[27] D. Pal, p 11.

7 ROTOR SIZE CALCULATIONS

To determine the proper rotor size, power available from the wind, in units of watts per square foot, should be calculated monthly for 1 year. Since all the kinetic energy available from the wind cannot be transformed into electrical power, an efficiency coefficient ranging between .32 and .35 should be used to determine the power extractable from the wind by a wind power generator.[28] Next, electrical load requirements, in units of kilowatt hours, should be determined monthly for 1 year. Thus, the rotor disk area required equals the average load demand divided by the average monthly power in the wind.

Once rotor area has been calculated, the monthly wind power generator output should be computed. This figure should then be compared to monthly electric demand loads. Oversupply can be computed to estimate storage requirements and undersupply will determine the backup power source required. The appendix provides an example of sizing a rotor. Figure 13 shows examples of wind power generators currently being tested, as well as their rotor size and annual energy output.

8 SYSTEM COMPONENT SELECTION

Once the system size has been established, system components should be selected. Components requiring further consideration include rotor blade construction, tower construction and height, transmission system, electric generator, power conditioning subsystem, and storage.

Blades

Propeller blades are designed in the form of airfoils and are generally straight and untwisted. They can be constructed of metal, wood, fiberglass, or a combination of these materials. Figure 14 illustrates materials and construction methods.

Tower Types

Table 5 summarizes the basic types of towers available.

Selection of an optimum tower height for a wind system should be based on cost per foot of tower and the gain in wind velocity per unit of increased

[28] William D. Metz and Allen L. Hammond, *Solar Energy in America* (Washington, DC: American Association for the Advancement of Science, 1978), p 125.

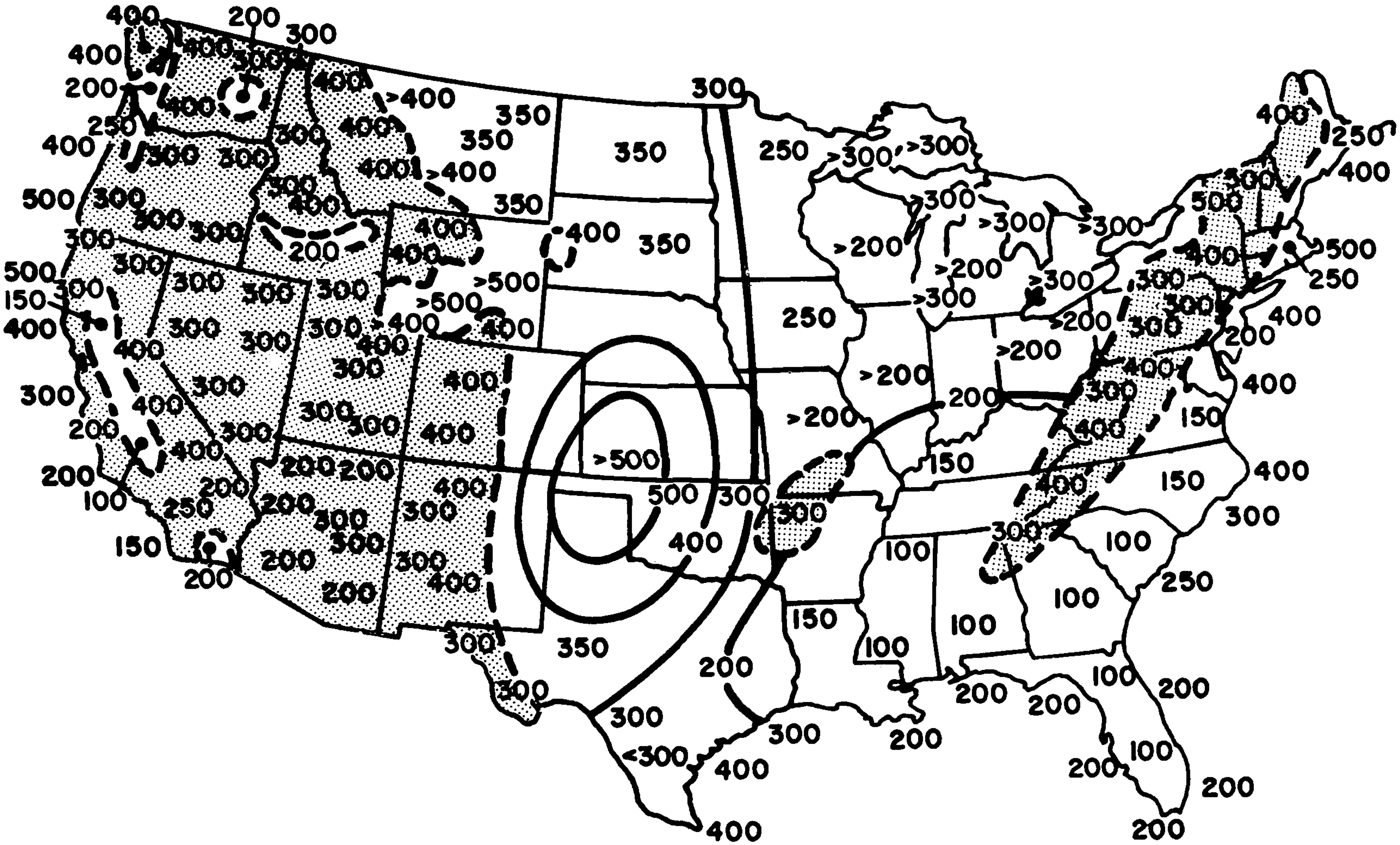
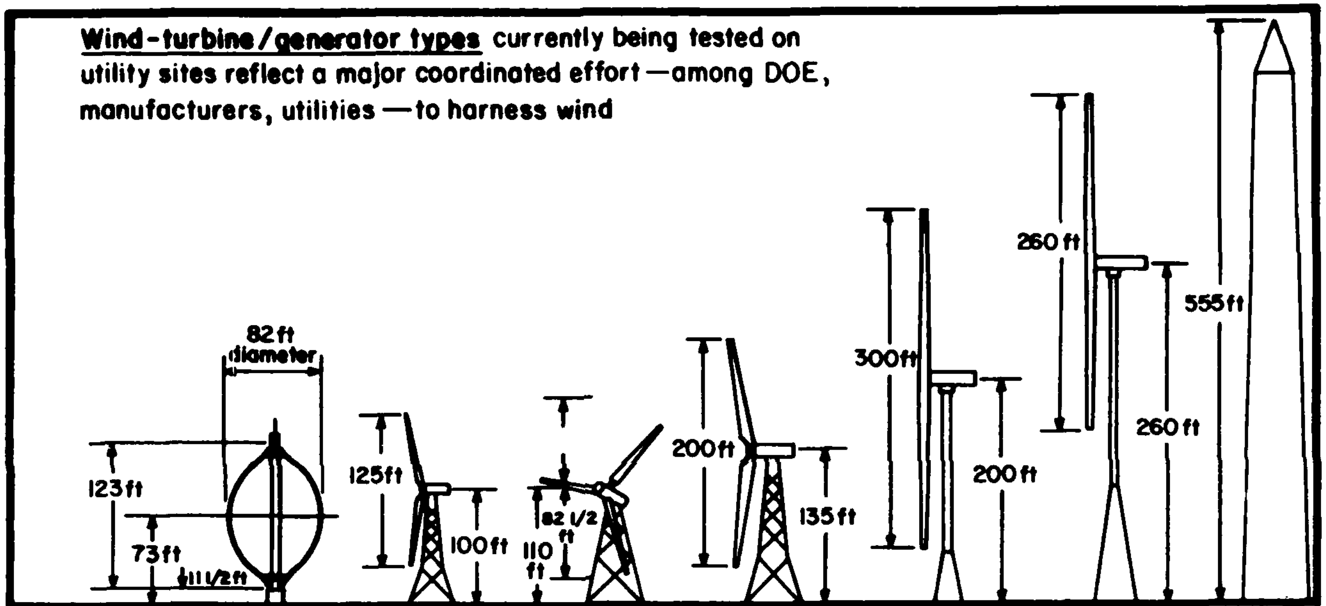


Figure 12. Annual mean wind power density in W m^2 estimated at 50-m elevation above exposed areas. Over mountainous regions, which are shown as shaded areas, the estimates are lower limits expected for exposed mountain tops and ridges. (From Gerald W. Koeppl, *Putman's Power From the Wind*, 2nd ed. [New York: Van Nostrand Reinhold Company, 1982], p 231.)



	Darrieus (vertical axis) (500 kW)	Mod 0 — Mod 0A (100 kW) (200 kW)	Bendix / Wind Power (Schachle) (3.0 MW)	Mod 1 (2.0 MW)	Mod 2 (2.5 MW)	Mod 4 Hamilton Standard (4.0 MW)	Washington Monument
Rated power (kw)	500	200	3,000	2,000	2,500	4,000	
Rated wind speed (mph)	26	17.3	40	25.7	19.5	—	
Rotor speed (rpm)	41	45	41	35	17.5	—	
Cut-in/cut-out wind (mph)	14/50	10/35	10.4	11/35	9/35	—	
Annual energy — million kWh	1.1	0.820	6	3.7	9.3	—	
At mean wind	15.6 mph	35 mph	17.8	14 mph	14 mph	*	

*This information is unavailable.

Figure 13. Wind-turbine generator types currently tested on utility sites reflect a major coordinated effort among DOE, manufacturers, and utilities to harness wind. (From Michael G. McGraw, "Wind-Turbine Generator Systems," *Electrical World* [May 1981], p 103.)

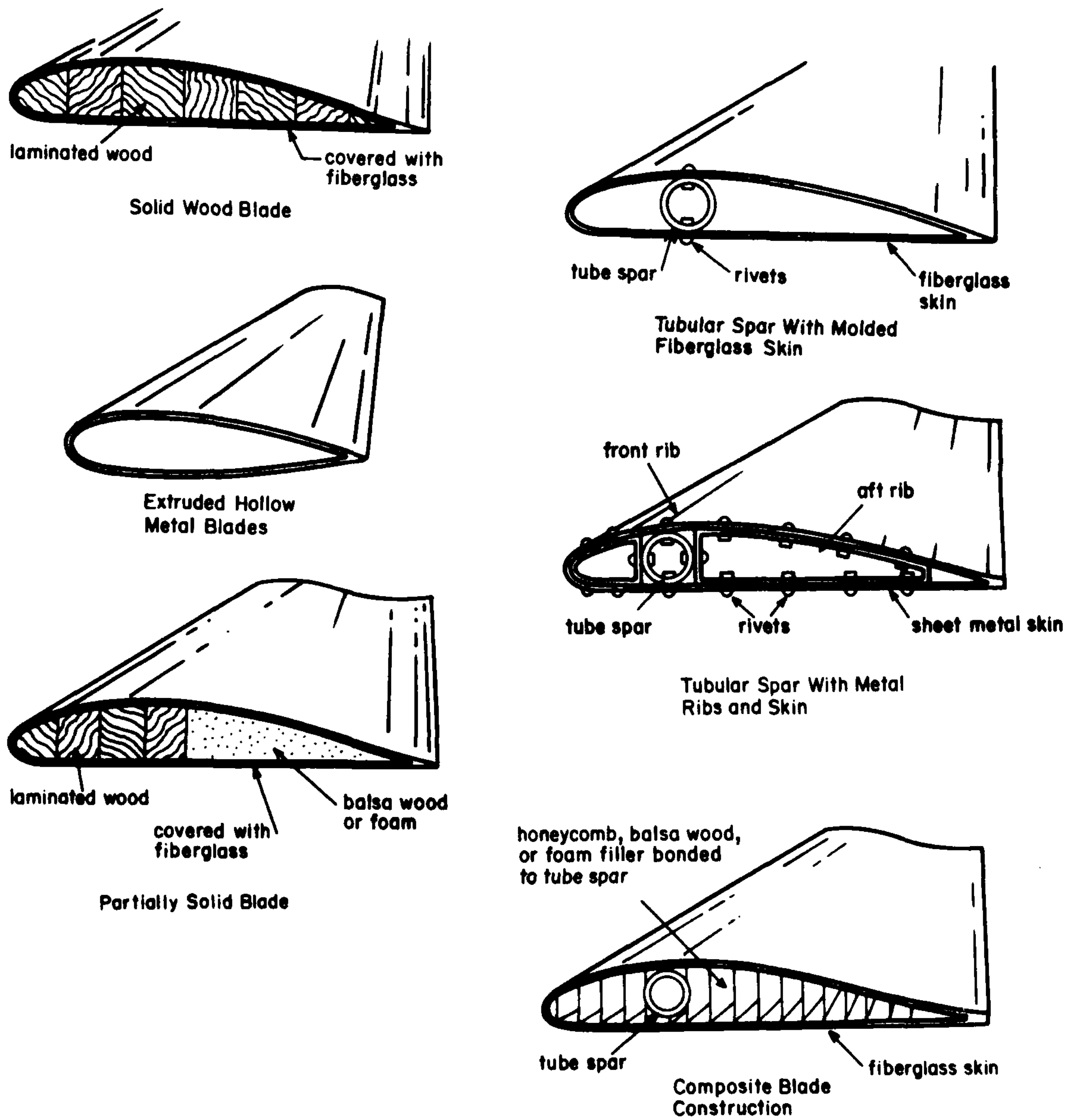


Figure 14. Different blade construction methods. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 77.)

Table 5
Various Tower Types for Wind Power Generator*

Type	Construction	Advantages	Disadvantages
Truss	Standard steel sections and connections	Readily available; most economical; easy modifications; small cost	Esthetics; exposed environment of the servicing steps
Reinforced Concrete	Truncated circular cone put into place using slip forms	Material and labor readily available	Heavy; expensive; poor properties require reinforcing steel; possible crack development
Steel Shell	Rolled conical sections which are field welded	Good esthetics	Most expensive type; erecting specialists required for construction
Guyed Pole	Circular steel or wood supported by steel cables	Provides strength against buckling	Poor esthetics; large land area required

*From D. Pal, *Wind Power Utilization Guide* (Port Hueneme: Naval Civil Engineering Laboratory Press, 1981), p 99.

elevation above the local ground. The recommended minimum blade clearance above the ground is 10 m.[29] Below this level, the amount of turbulence increases, operational safety becomes questionable, and the mean wind velocity decreases considerably. On a good hilltop site, tower height may be kept to this minimum level. Increasing tower height in open-level rural areas where there is a low mean wind velocity is advantageous if tower costs are small compared with total system cost. The extreme case for justifying a tall tower is a site on the fringe of an urban area. Along coastal areas, modest increases in tower height can be justified. Table 6 lists the optimum tower heights for a 20-kW wind power generator in various settings: three ratios of tower cost to system cost are given.

Transmission Systems

Transmission systems may either be fixed-ratio gearbox, beltdrive, chaindrive, or hydrostatic drive. Most wind power generators use the fixed-ratio gearbox. Gearbox transmissions are well-developed, provide excellent efficiency, and are highly reliable up to levels greater than 1000 kW. Belt and chain transmissions are not as efficient as gear transmissions and have not been used extensively in wind power systems. Hydraulic transmissions are very inefficient and have very limited use in wind power generator systems.

[29]D. Pal, p 100

Table 6
Optimum Tower Heights for a 20-kW Wind System in Various Terrains

Terrain Types	Optimum Tower Height (ft) When Ratio of Cost of a 33-ft Tower to Total System Cost Is—		
	0.1	0.2	0.3
Suburban Area	77	58	50
Level Terrain	65	44	35
Low-Level Coastal Sites	67 to 75	48 to 53	38 to 43
Good Hill Sites	60 to 65	38 to 44	33 to 35

Notes:

Site annual average wind speed at 33-ft height = 10 mph
Rated wind speed for the wind system = 20 mph
Cut-in wind speed for the wind system = 8 mph
Shut-down wind speed for the wind system = 50 mph
Rated power = 20 kW
Power at cut-in = 1.6 kW

Energy Conversion

The following factors should be reviewed when considering conversions of wind energy to electrical energy:

1. Type of output desired:
   a. Direct current (DC)
   b. Variable frequency alternating current (AC)

   c. Constant frequency AC.
2. Wind turbine rotational speed:
   a. Constant speed
   b. Nearly constant speed or variable slip
   c. Variable speed.
3. Use of electrical energy output:
   a. Battery storage
   b. Other forms of storage
   c. Interconnection with AC grid.

The following sections explain the components needed to convert wind energy to electrical power.

Electric Generators

Wind power generators smaller than 2 kW generally use DC generators. Wind systems greater than 2 kW can use one of three types of generators to produce AC power: synchronous generator, induction generator, and a DC generator with an inverter to produce AC power. The synchronous generator is the most attractive since it is readily accepted and well understood by utility companies. It also supplies needed reactive power for the loads and the transmission network for voltage support and regulation. This generator is slightly more efficient than other systems and is readily available.

DC generators are advantageous because operation and control problems are less complex. DC generators can accommodate, with a manageable range, a large mechanical torque variance with some output voltage variation. However, DC power must either be used directly or an inverter must be provided. The latter action increases system costs. In general, DC systems cost more per kW generated than other types of electromechanical converters.

An induction generator does not require precise synchronization when it is connected to the network. Because of its variable slip operation, it is more tolerant of wind gusts; it also provides better stability and damping characteristics when linked to a utility network. It is less expensive than the synchronous generator for systems of 1000 kW or more. However, induction generators need power factor correction capacitors on the power line; these capacitors deter the excessive reactive current flow produced when current is drawn from the line for its excitation. There is an automatic loss of excitation if the generator is separated from the network, and there is no direct way to control voltage.

Power Conditioning

The uncertain nature of wind velocity causes the wind power generator rotor to turn at variable speeds; thus, the generator delivers electricity with variable voltage and frequency. However, the use of power conditioning systems makes it possible to obtain constant voltage and frequency from wind energy conversion systems. The following sections list and explain a variety of power conditioning systems.

DC Motor-Driven AC Generator

This system generates DC power from the wind when used with a DC generator or a variable-speed AC generator with a transformer-rectifier unit. DC power is stored in batteries and may be used to operate a DC motor-driven synchronous or induction generator.

Solid State Inverter

This system sends both wind and auxiliary power through a control panel either for immediate DC use or for DC battery storage. If an AC load is required, power is sent to a DC-AC inverter by the control panel. This system is self-contained and supplies uninterruptible power as required.

Synchronous Inverter

This system takes the rectified output of an AC wind generator through an inverter system and feeds it to the existing grid lines. The inverter system converts DC wind power to AC power. The AC power is sent to the AC grid, where it is fixed at the voltage and frequency of the grid lines. Excess power then flows into the grid network, which serves as a storage device. The load obtains power at the voltage and frequency fixed by the grid lines. However, the existing grid strengths must be three to four times that of the integrated wind generator.

Field-Modulated Alternatives

This system, which is still under development, would direct wind power to a variable-speed, constant-frequency generating system. Modulation would result from AC excitation or control input from the existing power line.

Automatic Load Matching System With a Variable Transformer

This system, which is also under development, can produce relative constant voltage at the load by passing generated power through a constant voltage autotransformer. The generator can then share loads with the existing power source.

Table 7 summarizes the cost of all five systems for 5-kW and 10-kW sites. Figure 15 shows the efficiency of the power conditioning systems. The load matching system is the least expensive and most efficient system, but it cannot provide constant-frequency power.

Table 7
Cost of Various Power Conditioning Systems for 5- and 10-kW Wind Generators

Type	Cost ($) for— 5-kW Generator	10-kW Generator	Comments
1. DC Motor-Driven AC Generator	3,500	5,000	High maintenance, commercially available
2. Solid-State Inverter	5,000	8,000	Low maintenance, high reliability; commercially available
3. Synchronous Inverter	2,000	4,000	Operates with an existing power grid only, commercially available
4. Field-Modulated Alternator	1,000	1,500	System still under development; not commercially available
5. CEL* Switching System With a Variable Transformer	1,000	1,200	System under development; does not provide synchronous power components, commercially available

*Developed by the Naval Civil Engineering Laboratory, Port Hueneme.

Storage Systems

Energy generated in excess of immediate power demands may be stored for later use at times when winds have diminished and power requirements are high. The most common type of energy storage system is the lead-acid battery. Batteries are advantageous because they are simple and require minimal maintenance. However, batteries are an expensive form of energy storage and have only 60 to 70 percent conversion efficiency. Other storage systems, rarely used, include compressed air storage, electrolysis of water to produce hydrogen, and pumped storage at hydroelectric sites.

On the other hand, excess energy output may be transmitted from the generator to an existing electric grid where the local utility company can purchase generated wind power at "buy back" rates. Excess power dispersed in this manner must meet local utility specifications, and if unsatisfactory, generated power must first be routed through a power conditioning system to obtain AC power at the voltage and frequency of the grid line. If this method proves to be most cost-effective, Federal guidelines for marketing must be followed.

9 CONCLUSION

This report has presented an overview of the preliminary analyses required before procuring a wind power generation system at Civil Works field operating sites.

Wind power generation systems are best applied at remote sites where average wind speeds exceed 10 mph. Although wind power generation systems have been developed from 1 kW to 2.5 MW, those ranging from 5 kW to 100 kW would be most appropriate for Civil Works field operating sites. Whether a wind power generation system is procured will depend on the system's ability to generate electrical power relative to its cost; however, an efficient system provides the potential for fossil fuel savings.

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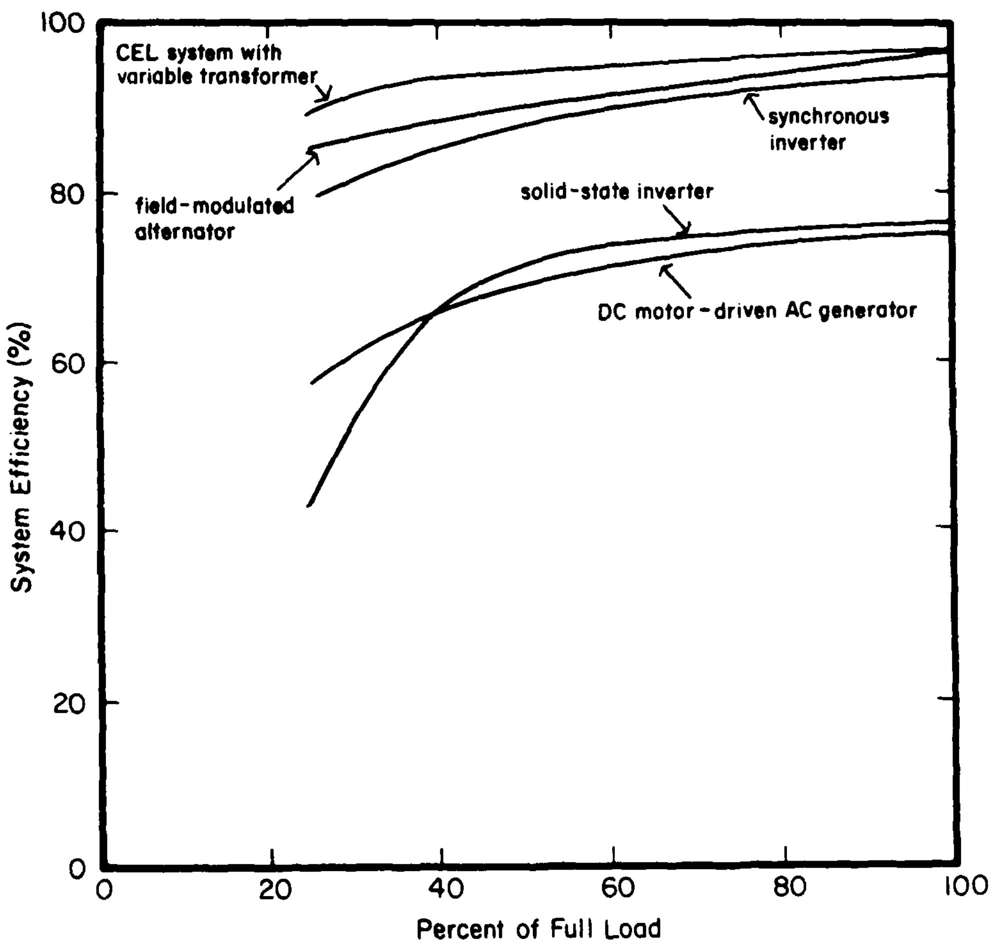

Figure 15. Efficiency of various power conditioning systems. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 113.)

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APPENDIX:

EXAMPLE OF SIZING A WIND POWER ROTOR

This example applies the calculations described in Chapter 6 for finding the adequate rotor size to supply enough electrical power to meet consumer demands. The example is a plan to displace purchased power with wind-generated power for space heating of a building at an installation near Buffalo, NY. Data which would have been previously collected by onsite analysis for determining the nature of the site's wind characteristics and the load requirement of the power system are:

1. The heating season is from mid-October to mid-April, lasting about 6 months.

2. The heating requirement is 575 MBtu per heating season (see Table A1).

3. The terrain is flat and homogeneous, with trees up to 30 ft tall.

4. The annual average wind speed for the site is 12.4 mph; the average value for the heating season (October to April) is 13.39 mph. Table A2 gives the monthly wind characteristics for the site.

5. The present cost of energy at the site is $0.08 kWh and the buy-back rate is $0.06 kWh.

The wind power generation system rotor size may then be calculated based on the average load requirement and the average available wind power. Hence, the turbine disk area required amounts to 1400.2 sq ft (8261/5.9), which implies a rotor diameter of about 42 ft. Table A3 shows the actual energy generated by such a wind generator system and the amount of heating load which may be displaced. The cost of heating energy displaced is calculated at $.08 per kWh. Excess energy is assumed to be sold back to the local utility at $.06 per kWh. The energy displaced by a wind power generation system amounts to about 87.74 percent of the total consumption (see Figure A1).

Table A1
Heating Requirement for the Season

Month	Heating Requirements MBtu	Heating Requirements kWh
October	36	3,103
November	85	7,328
December	98	8,448
January	108	9,310
February	108	9,310
March	115	9,914
April	25	2,155
Total	575	49,568
Average = Total / No. of months	95.83	8,261

Table A2
Wind Characteristics for Site

Month	Average Wind Speed (mph)	Power Available in the Wind (W/sq ft)	Power Extractable From the Wind System* (W/sq ft)
October	11.5	15.4	4.9
November	13.3	21.0	6.7
December	13.5	23.2	7.4
January	13.5	23.5	7.5
February	13.9	23.9	7.6
March	14.1	27.3	8.7
April	13.2	22.1	7.1
May	11.9	14.9	4.8
June	11.6	14.1	4.5
July	11.1	12.3	3.9
August	10.5	11.0	3.5
September	11.1	13.5	4.3
Average	12.4	18.5	5.9

*Overall power coefficient for system 0.32

Table A3
Actual Energy Generated and Displaced by Wind Power Generation System
With a Rotor Diameter of 42 Ft

Month	Wind System Output (kWh)	Heating Requirement (kWh)	Amount of Power Required After Displacement (kWh)	Cost of Energy Displaced ($)	Price of Energy Sold ($)
October	5,082	3,103	0	248	119
November	6,703	7,328	624	536	0
December	7,648	8,448	800	612	0
January	7,751	9,310	1,558	620	0
February	7,122	9,310	2,189	570	0
March	9,008	9,914	905	721	0
April	7,052	2,155	0	172	294
May	4,916	0	0	0	295
June	4,418	0	0	0	270
July	4,061	0	0	0	244
August	3,628	0	0	0	218
September	4,309	0	0	0	259
Total	71,778	49,568	6,076	3,479	1,699

Notes:

$$\text{Rotor disk area required} = \frac{\text{Average load demand}}{\text{Average monthly power in the wind}}$$

$$= \frac{8,261}{5.9} = 1,400.2 \text{ sq ft}$$

Rotor diameter required = 42 ft

Usable energy generated by the wind system = 49,568 - 6,076

= 43,492 kWh

$$\text{Percent of usable energy generated by wind system} = \frac{43,492}{71,778} = 61$$

Total monetary amount gained by wind system = 3,479 + 1,699

= $5,178

METRIC CONVERSION CHART

1 foot = .304 meter
1 mile = 1.6 square kilometers
1 acre = 4.05 square kilometers
1 mile/hour = .447 meters/second
1 pound = .45 kilogram

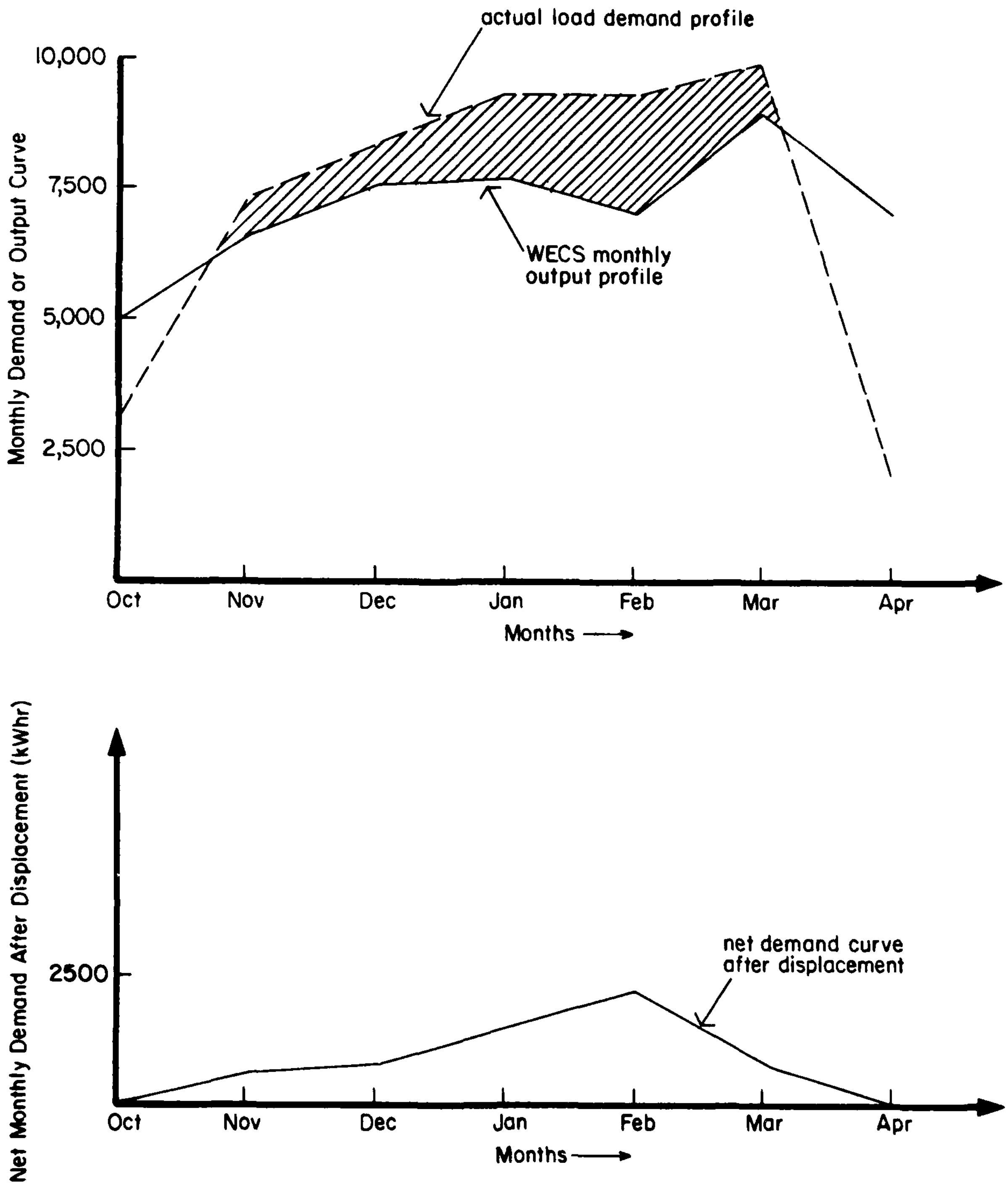

Figure A1. Monthly demand, wind system output, and net demand after displacement. (From D. Pal, *Wind Power Utilization Guide* [Port Hueneme: Naval Civil Engineering Laboratory Press, 1981], p 157.)

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